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Computer Control of a Scanning Electron Microscope for Digital Image Processing of Thermal-Wave Images

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COMPUTER CONTROL OF A SCANNING ELECTRON MICROSCOPE FOR DIGITAL IMAGE PROCESSING OF THERMAL-WAVE IMAGES

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SUMMARY

Using a recently developed technology called thermal-wave microscopy, NASA Lewis Research Center has developed a computer controlled submicron thermal-wave microscope for the purpose of investigating III-V compound semiconductor devices and materials. This paper describes the system's design and configuration and discusses the hardware and software capabilities. Knowledge of the Concurrent 3200 series computers is needed for a complete understanding of the material presented. However concepts and procedures are of general interest.

INTRODUCTION

Computer control of a scanning electron microscope (SEM) has several applications. These applications may include beam control for electron beam lithography or image processing of various signals from the SEM. Signals for image processing may include secondary electron, x-ray microprobe, backscattered electron, electron-beam-induced current, or thermal-wave images. Thermal-wave imaging is particularly interesting to material scientists or process engineers in that the thermal-wave images can provide information on subsurface thermal features of solid samples. Furthermore, thermal-wave microscopy (TWM) is a nondestructive technique yielding information not available by other techniques (ref. 1).

However, TWM is limited by low signal levels, extremes in signal contrast, and poor edge feature definition. Digital image processing can contribute significantly toward solving these problems (ref. 2). Furthermore, since TWM is a subsurface technique, three-dimensional imaging is possible using only digitization and frame manipulation.

SEM CONFIGURATION

To address any of these areas, it is necessary to digitize image frames and manipulate the frame data. One approach to this is to use a computer to control the SEM and collect signals. The computer retrieves an analog signal for each electron beam position and these signals are processed for noise

reduction and image enhancement. The beam position, delay before and after recording data, data recording, and manipulation are performed by the computer.

The purpose of this technical memorandum is to describe an implementation of this approach at NASA Lewis. A Concurrent 3205 (formally Perkin-Elmer) computer is used to control an ISI (International Scientific Instruments) DS-130 SEM. First a short description is given of the system configuration including the SEM hardware for TWM and interface to the computer. Next the user software and the special system drivers are described. Finally, examples of digital image processing applied to TWM will be given.

Figure 1 is a schematic representation of the modified SEM-computer system used to perform TWM. Thermal-wave imaging is accomplished by generating thermal waves in a specimen using an intensity modulated electron beam. Typical modulation, or beam blanking frequencies are 0.1 to 10 MHz. The thermal waves are critically damped but they do interact with thermal features (fig. 2). The acoustic waves, generated by the thermal waves, are detected in the following way. A sample is glued to an acoustic transducer. The transducer signal is amplified and then routed to a lock-in amplifier. The lock-in amplifier output is fed into channel no. 1 of the Concurrent 3205 analog to digital converter input. The Concurrent 3205 analog input is set to record signal levels between ±5.12 V. The computer controls the SEM through the x-ray microanalyser port of the SEM. One control line takes scan control of the beam from the SEM allowing the computer to position the electron beam. By supplying the two analog voltage levels for X and Y scan directions to the SEM at this port, the computer may position the electron beam at any point in the "normal" scan field. "Normal" here indicates that the SEM is using internal scan ramp generators for X and Y beam positioning. Therefore a typical event flow is as follows: (1) the computer takes scan control from the SEM, (2) the computer outputs analog X and Y scan voltages to the scan coils for the first beam position, (3) a predetermined delay time occurs, (4) the signal level into channel no. 1 is recorded into the data array, (5) a second predetermined delay time occurs, (6) the computer outputs analog X and Y scan voltages for the next position, (7) the system repeats steps 3 to 6 until the entire array of beam positions is accessed, then the computer releases scan control back to the SEM. The array of signals recorded by channel no. 1 make up the image frame when properly positioned by the X and Y scan coordinates. If the event flow above is repeated a number of times, the image frames may be added together to perform linear integration.

After the image is acquired and processed, it may be returned to the SEM for display and photo recording. The event flow is that listed above except steps 3 to 5 are replaced with outputting the analog signal for a predetermined delay time. The image frame may be output this way continuously as needed for viewing or photographing. The signal is adjusted for level and contrast by a video amplification at the input of the SEM.

SOFTWARE

The two mainline programs developed to provide image processing of incoming analog signals are called IMAGE1 and IMAGE2. These programs are compatable with the FORTRAN 77 compiler. IMAGE1 and IMAGE2 use special software drivers named SEM1 and SEM2 developed in-house to control the movement of the electron beam. These drivers do this by means of SYSIO, a standard FORTRAN 77

routine. The routine serves as a translating input/output medium. Programs IMAGE1 and IMAGE2 differ only in the system software driver used. IMAGE1 calls SEM1 and IMAGE2 calls SEM2. SEM2 uses a different method of storing data than SEM1 so it can handle larger scans. This and other differences are discussed in more detail later. These drivers and the ALLOCATE, ASSIGN, and CSS commands described next are peculiar to the Concurrent 3200 series computers (ref. 3).

The mainline user software programs, IMAGE1 and IMAGE2, read and write data to a file on the computer's hard disk. The file must be created before the program is loaded. The

ALLOCATE fd,IN,Lrec

command accomplishes this where fd is the file descriptor or name of the file to be allocated. IN specifies that the file type is an indexed file and Lrec is a decimal number specifying the logical record length in bytes of the file. If the file was previously defined, an error occurs and command processing is terminated. The ALLOCATE command is used to create each file for data storage on the disk.

After creating the files, a logical unit (lu) is assigned to each filename. The ASSIGN command assigns, or identifies, a file to a current logical unit on the system. The logical unit number is used in the program's FORTRAN I/O statements to access a specific file. Logical unit numbers -14 are available except for 0, 3, 4, and 5 which are reserved. The format is

ASSIGN lu,fd.

Using the efficiency of the command substitution system (CSS), the file assignments need be done only once. The user creates a CSS file and assigns the logical units to the filename as described above. The format should be

ASSIGN lu,@#

where @# is a dummy variable representing the filename. For example, if two files are allocated using the ALLOCATE command, then the two files are assigned in the CSS file as

ASSIGN lu,@1

ASSIGN lu,@2

where @1 and @2 are variables representing the two files created. To execute IMAGE1 or IMAGE2 with the above format, one enters

IMAGE1 filename1,filename2 or

IMAGE2 filename1,filename2

Where IMAGE1 and IMAGE2 are CSS files, designated as IMAGE1.CSS or IMAGE2.CSS, and filename1 and filename2 are the files allocated earlier.

Execution of IMAGE1 or IMAGE2 proceeds from this point. IMAGE1 is considered in detail as exemplary.

The IMAGE1 program enables the user to digitize images from the SEM. An image is digitized as the analog data is acquired and then converted to integer form for each position where the electron beam has scanned the entire frame. IMAGE1 is organized such that the main program allows the user to branch into any one of seven subprograms (fig. 3). The screen displays a menu of seven items representing the subprograms. The subprograms are

(1) Number of Pixels, Dwell Time
(2) Single Frame Scan
(3) Multiple Frame Scan (Averaging)
(4) Display
(5) Store
(6) Recall
(7) Stop

The first subprogram, "Number of Pixels, Dwell Time," establishes the data used by SYSIO for beam positioning and timing of movement. In response to "number of pixels" and "number of rows" the user enters values for the number of columns, N, and number of rows, M, of pixels. (Each pixel or picture element resides at the intersection of a row and a column, and may be identified by its column number and its row number.) The distance between columns is equal to the distance between rows.

The input in response to the "delay" is two delays each in integer*4 format. The first delay is the time between the movement of the electron beam to a pixel and the recording of the analog signal at channel no. 1. The second delay is the time for the movement of the electron beam to the next pixel location. A complete discussion of the format of the delay is given in "Specialized System Drivers" section. Following the assignment of row and column numbers for the pixel grid (M and N), the X and Y arrays are constructed. The X-array is used by SYSIO to control the horizontal movement of the electron beam, and the Y-array will be used to control the vertical movement of the electron beam. The X-array, the Y-array, and the data array (signal values read from channel no. 1) each contain M x N integers. All three arrays are placed into one large array called INCT, a parameter of SYSIO, with the first M x N locations occupied by the X-array, the next M x N locations occupied by the Y-array, and the last M x N locations occupied by the input data array. The first X value and the first Y value identify the first pixel in the frame. The second X value and the second Y value identify the second pixel, etc. Therefore, the size of the INCT array is 3(M x N). At the beginning of the IMAGE1 program, the initial starting point of the electron beam is designated by the value of INP. This value is given in volts and corresponds to the upper left hand corner of the image. Typical scan voltages are -4 to +4 V for Y and -5 to +5 V for X.

The second and third subprograms are "Single Frame Scan" and "Multiple Frame Scan (Averaging)" respectively. These routines are similar in that each calls SYSIO for beam movement and signal collection. They differ in the number of times they call SYSIO and the number of frames collected. The number of repetitions and therefore number of calls to SYSIO, or scans performed by the electron beam, is determined by the controlling parameter called NUM. When the "Single Frame Scan" subprogram is selected, NUM is set equal to one (1), and therefore, only one (1) scan is performed. When the Multiple Frame Scan" subprogram is selected, NUM is entered by the user and that becomes the number of scans performed. "Multiple Frame Scan (Averaging)" allows the user to average any number of frames together for noise reduction.

The image averaging operation produces an image that is the average of a number of frames. Each frame is scanned as a single frame scan. The scan process is controlled by SYSIO as follows: the electron beam addresses a pixel location and waits for a time equal to delay no. 1. An analog signal is read from channel no. 1. The beam then waits for a time equal to delay no. 2 and addresses the next pixel location and the process is repeated. This process continues until the electron beam has addressed each pixel location and data has been read from each location. In this way a single image frame is recorded. Each pixel of each frame is averaged with the corresponding pixel in the other frames. The resultant image will be a sum of images with a decrease in noise due to the random nature of noise.

Subprogram no. 4, "Display," allows the user to send acquired and processed image frames to the SEM for viewing. The display routine is similar to the multiple scan routine in that it uses the system FORTRAN I/O routine SYSIO. However instead of reading data at each pixel location, the "Display" routine outputs an analog signal voltage and X-Y scan voltages for each pixel location.

Subprograms no. 5 and no. 6 are for writing to, and reading from the hard disk. Item no. 5 is the "Store" routine. "Store" enables the user to store an image in a file at the logical unit designated by the CSS for that file. For example, to write to file "TST1", which is assigned to the logical unit number 5, the command is:

```
      Write(5,10) Data
10    Format(I#).
```

Here "5" is the logical unit number, "10" is the format label, "Data" is the variable containing the signal value at a particular pixel to be stored and I# is the number of integers found in the data being stored. This statement must be completed for each signal value of the image array being stored in the computer's memory or M x N times. In IMAGE1 the data found in the last (M x N) positions of the INCT array is written to the computer's hard disk along with the values of N, the number of columns and M the number of rows. The row and column values are stored first, followed by the data.

Subprogram no. 6 is "Recall" and is used to retrieve an image stored in a file on the computer's hard disk. To read from the file "TST1" assigned to logical unit no. 5, the following command is used:

```
      Read(5,10,Rec=1,ERR=100)Data
10    Format(I#)
```

Here "Rec" is the record pointer, "ERR" is the error label, "Data" is the variable accepting the image to be stored in memory, and I# is the number of integers found in the data being read from memory. In IMAGE1 the first two items read from the file are the values of the number of columns and rows found in the stored image. The data is then read from the file, one value at a time into the last (M x N) locations of the INCT array.

Subprogram #7 is "Stop". If selected, the program terminates execution and control is returned to the command mode of the computer system.

SPECIALIZED SYSTEM DRIVERS

The "Single Frame Scan," "Multiple Frame Scan," and "Display" subprograms utilize specialized software driver subroutines accessed by SYSIO to control the movement of the electron beam and to record or display image frames. There are two versions of the software driver subroutines and they are referred to as SEM1 and SEM2. The drivers differ for the most part in the size of X and Y data arrays. This section describes the driver subroutines and explains how they are called by the IMAGE1 and IMAGE2 programs. The discussion begins with SEM1.

The computer must position the beam, read the analog data, and repeat these tasks for each beam position. Furthermore, as these tasks are to be performed as fast as possible except for programmed delays, the special driver subroutines are used eliminating the need to go to a call routine for each point. The driver is called once for each frame scanned and uses a FORTRAN SYSIO (ref. 3) statement:

```
CALL SYSIO(PBLK,Y'45',LU,INCT,NUMVAL,Y'1001',DELAY).
```

Here PBLK is an integer*4 argument that signifies the normal function code, Y'45', for recording data. LU is an integer*4 argument that specifies the logical unit that is assigned to the device SEM:. The symbol INCT is an integer*2 array containing the following data:

- The first (M x N) values shall be the X-axis D/A output values.
- The next (M x N) values shall be the Y-axis output values.
- The final (M x N) locations contain the analog values read at each X-Y point.

NUMVAL is an integer*4 argument that is equal to 2*(M x N) or twice the number of pixels.

Y'1001' is an integer*4 argument that contains the A/D gain and channel number. Bits 0, 1, 2, and 3 of Y'1001' are the gain bits with the following definitions:

0000 - Sample addressed at gain setting used for last channel
0001 - Sample addressed channel at gain of 1
0010 - Sample addressed channel at gain of 2
0011 - Sample addressed channel at gain of 8

The A/D board is presently hardwired for a full scale voltage of ±5.12 V; therefore

Gain	Volts full scale	Resolution at 12 bits
1	±5.12	2.5000 mV/bit
2	±2.56	1.2500 mV/bit
4	±1.28	.6250 mV/bit
8	±0.64	.3125 mV/bit

The address bits are 4 to 15 and select the channel to be sampled. The channel sampled is t±0.64he decimal value of bits 4 to 15. For example:

If bits 4-15 = >0000 0000 0000, then the sample channel addressed is 0
If bits 4-15 = >0000 0000 0001, then the sample channel addressed is 1
If bits 4-15 = >0000 0000 0010, then the sample channel addressed is 2
If bits 4-15 = >0000 0000 0011, then the sample channel addressed is 3

Therefore Y'1001' addresses channel 1 at a gain setting of 1.

DELAY is an integer*4 argument that contains the two delays. The first delay is the time delay between the beam movement and the reading of the analog voltage. The second delay is the time delay between the reading of the analog voltage and the movement of the beam to the next point. The first 16 bits of this argument is delay one, and the second 16 bits is delay two. Note that the bits are numbered from 0 to 15 from left (MSB) to right (LSB). Each delay is made up of two parts: the resolution and the interval count. The first four bits (0 to 3) define the resolution:

Bit 0 - 1 ms
Bit 1 - 100 µsec
Bit 2 - 10 µsec
Bit 3 - 1 µsec

Only one of these four bits should be set in order to select the resolution. If more than one of these bits are set, the driver will reject the call and return a status of X'F200' in the status location in the array PBLK. Bits 4 to 15 specify the interval count. The delay is therefore calculated by multiplying the interval count by the value of the resolution selected. The maximum value of the interval count is 4095 (all bits 4 to 15 set). A delay of one (1) or zero (0) at any resolution is not permitted. The driver will reject the call and return a status of X'F000' in the status location in the array PBLK. A delay of less than 32 µsec is not permitted. It will be rejected and a status of X'F100' will be returned. When either delay is set to zero (i.e., all 16 bits are zero) the delay program code in the driver is bypassed, producing the shortest delay possible.

Note that although the requested delays can be as short as 32 µsec, there is an inherent (overhead) delay in the driver. This overhead is 150 µsec for each delay when a delay value is specified. The overhead is 60 µsec when the delay specified is zero. Therefore, the minimum actual delay between points is approximately 300 µsec plus the requested delays when both delays are nonzero, and 120 µsec when both delays are zero.

In the subroutine call, Y'45' represents the normal function code to record data. A number of other function options exist as well. The code Y'46' directs the driver to write out the data in the same format in which it was read. The Y'46' function code is used when the 'Display' option is selected because it enables the user to view acquired data on an external device such as a video monitor. The following are additional function codes and their uses:

Y'84' - Turn write-thru signal ON (zero voltage)
Y'82' - Turn write-thru signal OFF (+5 V)
Y'90' - Turn nonstore signal ON (zero voltage)

Y'A0' - Turn nonstore signal OFF (+5 V)
Y'88' - Trigger the erase pulse

When the driver subroutine is called by IMAGE1 a status code is assigned. Depending on the validity of the call statement, the status code has the following meaning:

X'0000' - No error; request has been executed
X'8600' - Incorrect address alignment of the data
X'C0xx' - Illegal function code (xx = offending FC)
X'F000' - Time delay request is one or zero at any resolution
X'F100' - Time delay of less than 16 μsec requested
X'F200' - More than one or none of the time resolution bits are set

SEM2 is similar to SEM1 and is called from a FORTRAN program in the same way. The call parameter arguments that are not specifically described here have the same meaning as those for SEM1. LU is an integer*4 argument that specifies the logical unit and is assigned to device SEM2: (note the colon indicating a device name). INCT is an integer*2 array with the following data in it:

- The first N values are the X D-A output values
- The next N values are the Y D-A output values
- The last 2*N locations are the values read at each pixel or X-Y point

Note that the beam will be scanned in the following sequence: X1-Y1, X1-Y2, X1-Y3, ... , X1-YN, X2-Y1, X2-Y2, X2-Y3, ... , X2-YN, ... ,X3-Y1, X3-Y2, X3-Y3, ... ,X3-YN, ... , XN-Y1, XN-Y3, ... , XN-YN. The total number of pixels addressed is N**2. However there is no Z-axis on/off control. The beam will be pulsed on at every point. All other parameters are the same as in SEM1.

The main advantage of SEM2 compared to SEM1 is that less program storage is required by SEM2 for the X and Y D-A control values. Using SEM1 to scan M by N points requires 2*(M x N) control values; (M x N) for the X-values and (M x N) for the Y-values. However this gain is with some loss of scanning flexibility. As described above points cannot be scanned in a totally random fashion when using SEM2. All function codes used and all status codes returned by SEM2 are the same as those for SEM1 as described in the previous section.

APPLICATION

As stated earlier, an example of the image enhancement capabilities of the IMAGE1 program is given for thermal-wave-microscopy applications. Using stainless steel as a sample, thermal wave microscopy images were obtained. The stainless steel was connected to a transducer/preamplifier inside the vacuum chamber of the SEM. The preamplifier was connected to a lock-in amplifier with the output of this lock-in amplifier going directly into channnel no. 1 of the Concurrent 3205 analog input. The video monitor of the SEM was connected to the analog outputs of the Concurrent 3205 computer.

A most useful aspect of the IMAGE1 program is the ability to reduce random noise by linear averaging. Linear averaging is performed by adding

several frames together and dividing by the number of frames. When adding frames, the true signal increases with the number, N, of frames added together. The noise is however random; the distribution of random noise is proportional to the square root of N for N samples. Therefore the improvement in the signal-to-noise ratio is proportional to the square root of N so that the net effect is to decrease the random noise.

Figure 4 is a 128 by 128 pixel thermal-wave micrograph of a single frame scan of a stainless steel sample. Figure 5 is the average of 16 frames of thermal-wave images. Notice the improved definition of the crystallite grains of stainless steel in the thermal-wave image. Figure 6 is an average of 100 frames of the thermal-wave image. The result is a greatly improved thermal-wave image with features more clearly visible. The improvement is due to the reduction of noise by linear averaging. Figure 7 is a secondary electron micrograph of the same area. Note that there are no grain features visible.

CONCLUSION

A Concurrent 3205 computer system is used to control an ISI DS-130 SEM. The written software positions the electron beam and collects signals for digital image processing. The programs IMAGE1 and IMAGE2 can linear average a number of image frames, store or recall frames from disk storage, as well as output the image frames for viewing on the SEM's CRT.

APPENDIX - GLOSSARY

CCUR	Concurrent Computer Corporation
CSS	Command Substitution System
IMAGE1	Name of first specialized user FORTRAN routine
IMAGE2	Name of second specialized user FORTRAN routine
ISI	International Scientific Instruments
SEM	Scanning Electron Microscope
SEM1	Name of first specialized system software routine
SEM2	Computer operating system device name (eg. plotter, printer)
SYSIO	I/O FORTRAN routine (CCUR extension)
TWM	Thermal wave microscopy

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   Multi-Terminal Monitor (MTM) Reference Manual. Perkin-Elmer Data Systems Group, Publication #48-043 F00-R02, 1984.

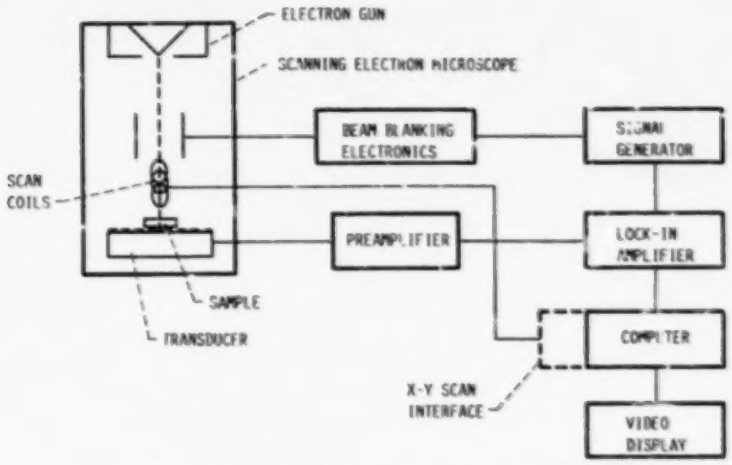

FIGURE 1. - PHYSICAL ARRANGEMENT OF TWM IMAGING SYSTEM.

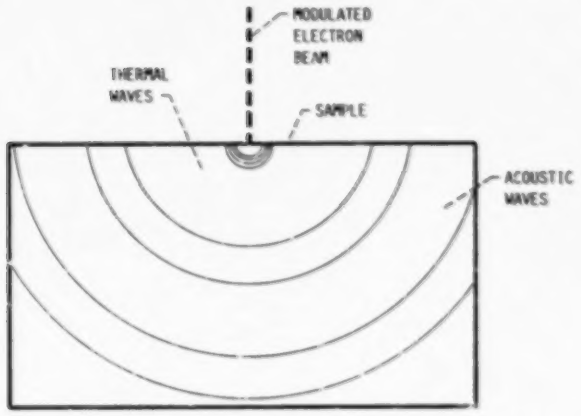

FIGURE 2. - THERMAL AND ACOUSTIC WAVES GENERATED IN A SOLID BY USING A MODULATED ELECTRON BEAM SOURCE.

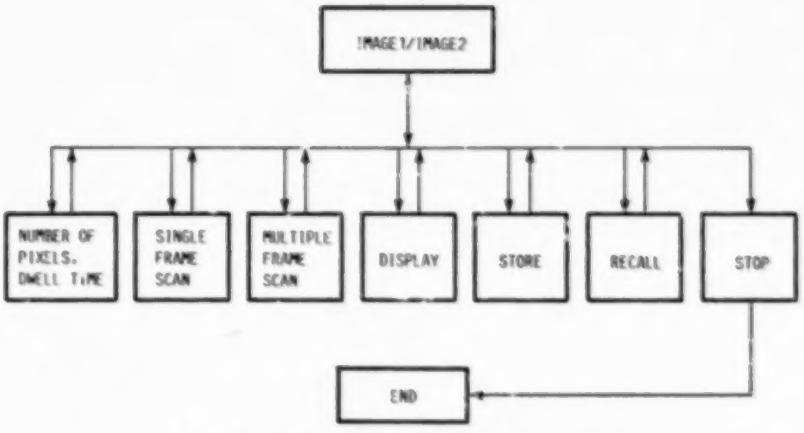

FIGURE 3. - TWM SYSTEM CONTROL SOFTWARE FLOW DIAGRAM.

FIGURE 4. - TWM IMAGE FOR 1 FRAME SCAN OF THE ELECTRON BEAM OVER A STAINLESS STEEL SAMPLE.

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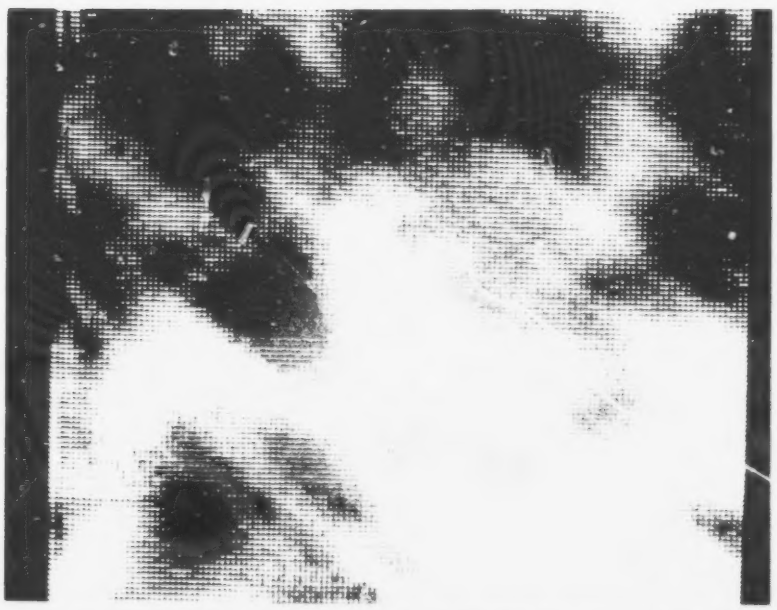

FIGURE 5. - TWM IMAGE FOR 16 FRAME SCANS OF THE ELECTRON BEAM OVER THE SAME AREA.

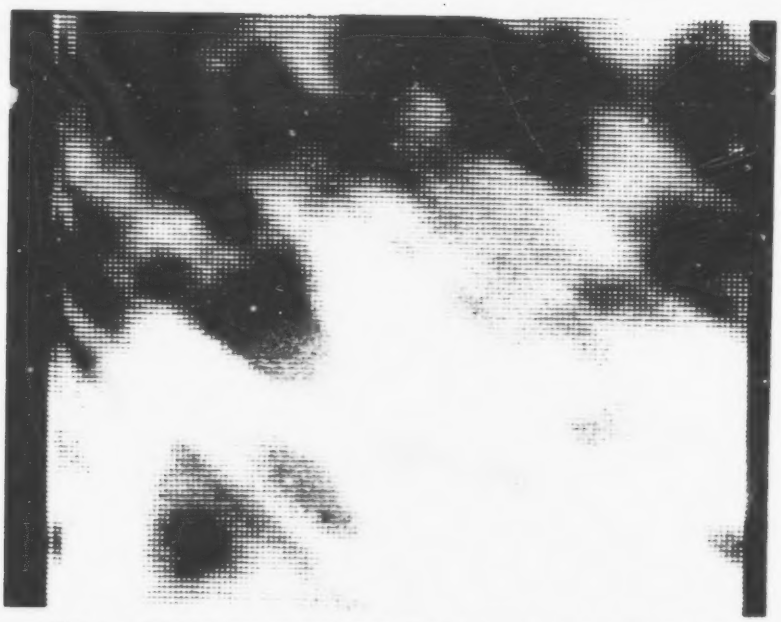

FIGURE 6. TWM IMAGE FOR 100 FRAME SCANS OF THE ELECTRON BEAM OVER THE SAME AREA.

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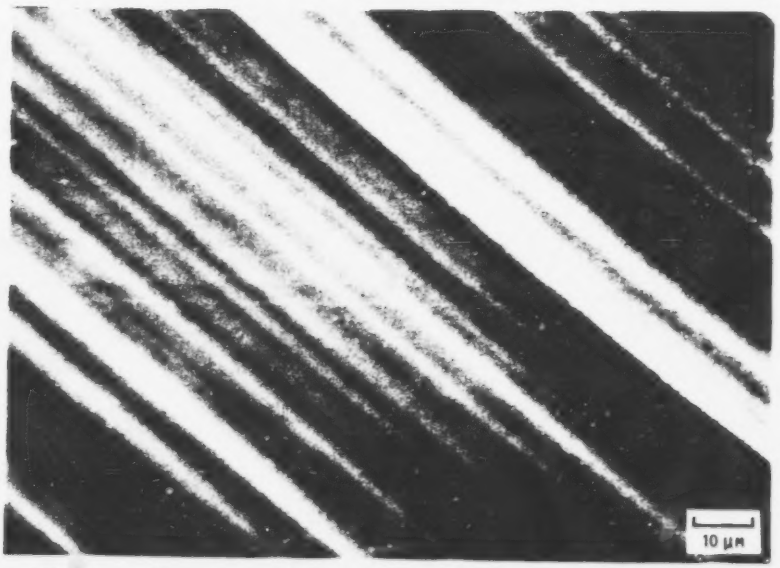

FIGURE 7. - SECONDARY ELECTRON IMAGE OF THE SAME AREA OF THE STAINLESS STEEL SAMPLE.

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16. Abstract

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